Int J Life Cycle Assess (2012) 17:863–875
DOI 10.1007/s11367-012-0409-8

LCA FOR AGRICULTURE

# LCA of a tomato crop in a multi-tunnel greenhouse in Almeria

**Marta Torrellas · Assumpció Antón · Juan Carlos López · Esteban José Baeza · Jerónimo Pérez Parra · Pere Muñoz · Juan Ignacio Montero**

Received: 1 October 2010 / Accepted: 5 March 2012 / Published online: 1 June 2012


**Abstract**

*Purpose* Protected crops have expanded significantly in the Mediterranean area over the last few decades as a successful means to provide abundant and high-quality produce. Although resources are generally used efficiently, greenhouse areas cause major environmental impacts. The aim of this work was to study, from an environmental point of view, the improvement capacity of greenhouse areas in the Mediterranean region and to assess several alternative agricultural practices to decrease their contribution to the environmental impacts in this system.

*Materials and methods* The methodology used was life cycle assessment (LCA) based on a tomato crop grown in a multi-tunnel greenhouse in Almeria, on the southeast coast of Spain. The functional unit chosen was 1 ton of loose classic tomatoes. Five midpoint impact categories and one energy flow indicator were selected for their relevance. The agricultural practice alternatives evaluated were reduction of volume of substrate and fertilizers, extension of substrate and greenhouse life span and increase in renewable energy for electricity production.

*Results and discussion* The results indicated that the main contributors to impact categories in the tomato production were structure, auxiliary equipment and fertilizers. Structure accounted for between 30 and 48 % of the contributions, depending on the impact category. The principal burdens in the auxiliary equipment stage were substrate and consumption of electricity. Fertilizers environmental impacts were due to emissions during their manufacture and application to the crop. In a best-case option, taking into account the best alternatives, contributions to the impact categories were reduced by between 17 and 30 %. The LCA methodology proved to be a useful tool to evaluate the environmental damage of this agricultural activity. The importance of including farm infrastructure in the assessment was demonstrated as it was a major contributor. The risk of eutrophication could be reduced by adjustment of the fertilizers–water balance and implementation of a closed-loop irrigation system. Future technological improvements should be developed to increase yields and thereby directly reduce the environmental burdens per unit produce.

*Conclusions* The present study served to assess the environmental impacts of a tomato crop in a multi-tunnel greenhouse on the coast of Almeria. The assessment was used to evaluate alternatives for improvement of cleaner production in greenhouse areas. Further research should focus on assuring the feasibility of the suggested options.

**Keywords** Environmental impacts · Fertilizers · Horticulture · Protected crops · Substrate

M. Torrellas (✉) · A. Antón · P. Muñoz · J. I. Montero
IRTA (Research and Technology Food and Agriculture),
Ctra. de Cabrils, km 2,
08348 Cabrils Barcelona, Spain
e-mail: marta.torrellas@irta.cat

A. Antón
Departament d'Enginyeria Química, Universitat Rovira Virgili,
Avda. Països Catalans, 26,
43007 Tarragona, Spain

J. C. López · E. J. Baeza · J. P. Parra
Estación Experimental de la Fundación Cajamar "Las Palmerillas"
Autovía del Mediterráneo,
km 416,7,
04710 El Ejido, Almeria, Spain

## 1 Introduction

Protected horticulture has increased considerably over the last few decades in areas such as the southeast of Spain, on

the Mediterranean coast. The main reason for this expansion was the arrival of plastics on the market, ideal for the construction of shelters in the climate conditions of the Mediterranean basin (FAO 2002), as well as in answer to the demand of vegetables from North Europe.

It has been demonstrated that protected horticulture produces a good harvest. Greenhouses have been extremely successful in providing abundant, cheap and high-quality produce, by using resources (water, minerals and pesticides) with a very high economic efficiency (Stanghellini et al. 2003). On the other hand, intensive production in greenhouses is perceived as a polluting activity because of the large amount of inputs required, waste generated and high-energy needs.

In terms of greenhouse management, there are differences between cold and warm climates. While the main environmental impacts of horticultural production in northern countries with a cold climate are due to energy consumption for heating and lighting, greenhouse production in southern countries with a warm climate has lower energy requirements and needs fewer inputs, apart from water and fertilizers.

A widely accepted methodology to evaluate the environmental impacts of agricultural systems is life cycle assessment (LCA) (Audsley et al. 1997; Cowell 1998; Nemecek and Erzinger 2005). LCA allows objective quantification of the environmental impacts of a product, process or activity and consequently is a useful guide when developing improvements. Many LCA studies have been conducted in glasshouses in northern countries (Van Woerden 2001; Williams et al. 2006; Jolliet 1993; Williams et al. 2008).

Jolliet (1993) evaluated energy consumption and environmental emissions for tomato production in seven different glasshouse scenarios in Switzerland. This study can be considered a precursor of LCA as the whole chain of tomato production was considered. The author suggested that processes with high energy consumption, such as heating and lighting, should be reduced, while an increase in production could result in a decrease in environmental burdens per kilogram of tomato. The conclusion was that production in southern countries is more favourable from an energy point of view even if transport to central Europe is added.

Van Woerden (2001) applied LCA in Dutch glasshouse horticulture to describe the environmental effects of future developments in crop production systems, and to compare organic and conventional horticulture. The author calculated the contribution of different inputs (glasshouse, crop protection, fertilizers, heating, etc.) to the total environmental impact of tomato cultivation in a greenhouse. The results showed that the use of energy was responsible for about 75 % of the total environmental impact of the crop and the contribution of the glasshouse structure over 10 %.

Williams et al. (2008) compared greenhouse loose classic tomato production in the UK and Spain. Burdens of energy use were 36 MJ $kg^{-1}$ in the UK and 8.7 MJ $kg^{-1}$ in Spain. Energy use was greater in the UK, and the burden always outweighed the extra transport and cooling needed to deliver tomatoes from the south of Spain to the UK by road.

In the Mediterranean basin, the area devoted to protected horticultural crops went from nil in the 1950s to 120,000 ha in 1985 and nowadays there are about 170,000 ha of greenhouses and high tunnels. Spain has the greatest covered area in Europe, with 50,365 ha of greenhouses. The largest concentrations of protected crops are in the southeast with nearly 60 % of the total greenhouse area in Spain in Almeria. Nearly 90 % of protected crops in Spain is devoted to vegetable crops; the rest being dedicated to ornamentals (EFSA-PPR 2009).

Some studies on protected crops in the Mediterranean region have focussed on energy consumption and environmental impacts (Stanhill 1980; Antón 2004; Romero-Gámez et al. 2009).

Stanhill (1980) assessed the energy consumption of tomato production in six different environmentally protected cropping systems, five in Mediterranean climate regions and one further north, concluding that horticultural development should seek to increase the exploitation of natural advantages rather than more sophisticated, and complete, control of the environment.

Antón (2004) used LCA methodology with a spring—summer tomato cycle, typical of crops in northern Spain, to study the environmental bottlenecks of the multi-tunnel Mediterranean greenhouse. This study identified the use of fertilizers and perlite as the main contributors to most impact categories.

Also in the Mediterranean area, Romero-Gámez et al. (2009) evaluated the environmental damage attributable to the cultivation of green beans in screen greenhouses with or without misting and in the open field. The authors demonstrated that greenhouse crops are environmentally justifiable, with a >15 % increase in yield compared with open-field cultivation.

Nowadays, high-technology greenhouses are being used in areas dominated by simple plastic greenhouses. Antón (2008) compared ‘parral’ and multi-tunnel greenhouse structures in the Canary Islands. The ‘parral’ greenhouse has a simple frame structure, resulting in lower environmental impacts than a multi-tunnel greenhouse, but there is little chance of improving crop yield and quality. Currently, the major protected area on the coast of Almeria is covered by these greenhouses and very small area is dedicated to multi-tunnel greenhouses (EFSA-PPR 2009). However, multi-tunnel greenhouses offer technological adaptation capacity with optimization of yields. Thus, from an environmental point of view, it would be better to assess potential cultivation improvements in a multi-tunnel greenhouse, with innovative developments and monitoring tools producing more efficient results in a high-technology greenhouse.

The present study is part of the EUPHOROS project (EUPHOROS 2008–2012), set up in response to concern about the sustainability of food production and co-financed by the Seventh Framework Programme of the European Union (EU). The aim of the 4-year project (2008–2012) is to develop sustainable protected horticultural and ornamental crops with a reduction of external inputs. The issues focussed on are the reduction of fossil energy, carbon footprint of equipment, water use, emissions from fertilizer manufacture and use, plant protection chemicals application and full recycling of substrate. High productivity and resource-use efficiency are also priorities. Research institutes and companies in the main European countries specializing in greenhouse crop production participate in this project.

Here, we used LCA to determine the environmental impacts of tomato production in a multi-tunnel greenhouse on the coast of Almeria. The objectives were to identify the major burdens that could be reduced and to evaluate the environmental impacts of several alternative clean designs. Although a multi-tunnel greenhouse was chosen for the study, most of the alternatives for improvement could also be adapted to other simpler greenhouse structures, such as ‘parral’.

## 2 Materials and methods

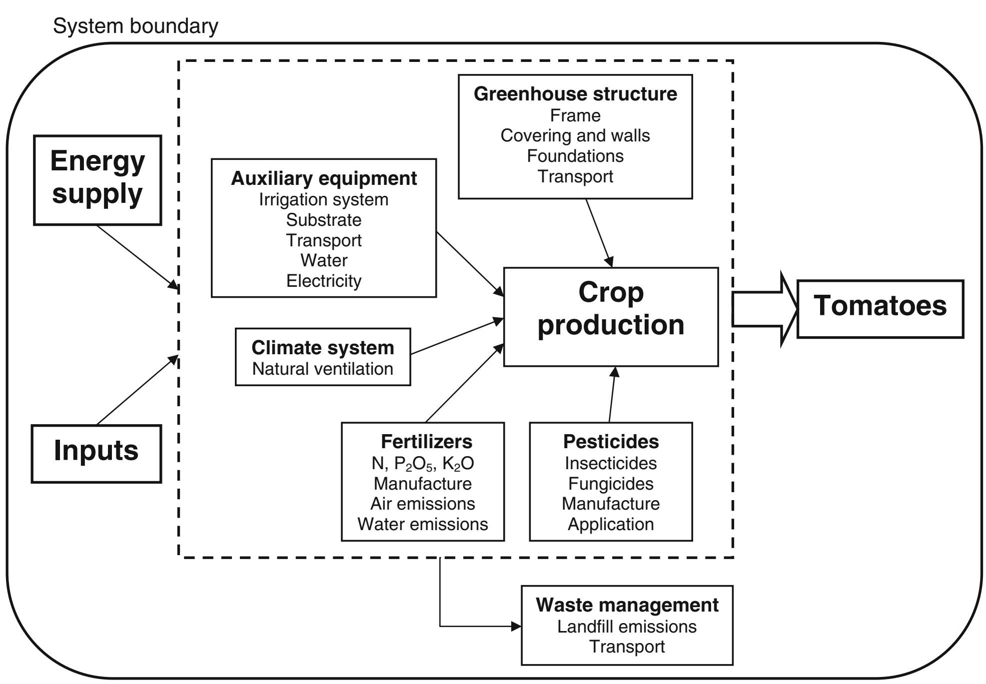
A loose classic tomato crop in a multi-tunnel greenhouse was selected for the study as representative of high-technology agricultural practices in the Mediterranean region. The methodology chosen to evaluate the environmental impact of the tomato production was LCA which has been effectively applied in agricultural and food systems over the last few years.

The functional unit (FU) refers to the main function of the system analysed and is the reference unit for the inputs and outputs of the system analysed. Since the final function was the production of vegetables, the FU chosen for this study was the mass unit 1 ton of loose classic tomatoes. An average production of 16.5 kg $m^{-2}$ was considered representative for this type of greenhouse structure in this area (Montero et al. 2011).

The system boundary defines the unit processes included in the model production system. We defined the system boundary from raw materials extraction up to farm level, including material disposal: neither post-stages nor marketing processes were taken into account in the study, as the aim was to improve means of production. The processes considered for the environmental analysis included inputs and outputs in the manufacture of greenhouse components, transport of materials, materials disposal and greenhouse management (water, fertilizers, pesticides and electricity consumption).

The crop production system was structured in several stages for the inventory analysis, each one including processes and flows, in order to facilitate the study and interpretation of the results: greenhouse structure, auxiliary equipment, climate control system, fertilizers, pesticides and waste management. A flow diagram for the production system is shown in Fig. 1.

**Fig. 1** Flow diagram for tomato production system in a multi-tunnel greenhouse



The data used for the inventory phase, in which inputs and outputs of the processes in the tomato production system were quantified, were from the period between 2006 and 2009. The specific data for the agricultural operations, such as water consumption, fertilizers and pesticides doses and yield, were experimental greenhouse data collected by the Estación Experimental de la Fundación Cajamar (Fundación_Cajamar 2008), situated on the coast of Almeria (2°43′ W, 36°48′ N, altitude 151 m). The greenhouse structure was modelled as a generic data set representing the typical structure of a multi-tunnel greenhouse. Data for the following processes were obtained from the Ecoinvent database (Frischknecht et al. 2007): manufacture of greenhouse components, substrate, and pesticides; electricity production mix; and materials transports, and disposal. The LCAFoods database (Nielsen et al. 2003) was used for fertilizer manufacture.

The SimaPro program version 7.2 was used for the environmental assessment, only performing the compulsory classification and characterization phases defined by the ISO 14040 (2006).

The indicators and impact categories selected for the environmental assessment were chosen because of their relevance in energy and agriculture processes and were: cumulative energy demand (MJ) as the energy flow indicator, and five midpoint impact categories, defined by the CML2001 method v.2.05 (Guinée et al. 2002): abiotic depletion (kg Sb eq), acidification (kg $SO_2$ eq), eutrophication (kg $PO_4^{-3}$eq), global warming over 100 years (kg $CO_2$ eq) and photochemical oxidation (kg $C_2H_4$ eq). Cumulative energy demand includes the direct and indirect energy use and is widely used as a screening indicator to point out the priorities of energy saving potentials throughout the life cycle of a good or service. Abiotic depletion is related to extraction of minerals and fossil fuels due to inputs in the system. Ammonia and nitrate emissions from N-fertilizers are important pollutants in acidification and eutrophication. Emissions related to agricultural inputs, mainly fertilizers and greenhouse structure, are important contributors to global warming, which is related to greenhouse gas emissions to air. Photochemical oxidation formation is a category that may have important consequences on agriculture (i.e. ozone contamination). Land use, water use and toxicity are other important impact categories in agriculture assessment, nevertheless they were not considered since there is no international consensus for their evaluation (Antón 2008; Berger and Finkbeiner 2010; ILCD 2010)).

The life span of the greenhouse was estimated at 15 years according to the European Committee for Standardization (CEN 2001) and the LCA conservative approach, as most growers usually extend life span of the greenhouse. Greenhouse life span refers to the lifetime of materials included in its structure, such as the steel frame, trellis wire, concrete foundations and polycarbonate walls (Table 1). The materials production processes were considered in the inventory. Processes such as the manufacture of steel and plastic elements, drawing of pipes, plastic extrusion and a coating treatment were taken into account. It was estimated that steel was mainly produced from recycled steel scrap (INVERCA 2011).

The main characteristics of the defined stages were as follows:

Structure—an 18-span greenhouse with a span width of 8 m and gutter and ridge heights of 4.5 and 5.8 m respectively. The steel elements were posts, frame reinforcements, gutters, axes, profiles, arches and ventilators. The trellis system to support the tomato crop was made of wire. The covering and floor mulching were made of low density polyethylene, the front and side walls of polycarbonate sheet and the insect proof screens of polyethylene. The foundations and main path were made of concrete (Table 2).

Auxiliary equipment—this included: the irrigation system; drainage and rain water collecting installations; consumption of electricity by the watering system, and the substrate. The irrigation system was an open-loop drip system, without recirculation of drainage water. The plastic components were the beds, pipes, drippers, micro tubes, stakes, the fertilizer tanks and the substrate layers. Steel elements were the injectors and the pumps. The substrate used was perlite in polyethylene bags of 30-l volume. Each bag contained three plants with two stems per plant, at a density of 1.2 plants $m^{-2}$. The growing period was considered 12 months, planting in September and harvesting from January to June and a 3 months resting period without crop. Electricity consumption by the watering system was 38.6 kWh·tomato $ton^{-1}$. The total amount of water consumed was 4,748 $m^3$ $ha^{-1}$ including a 25 % watering surplus to avoid build-up of salts, giving a water use of 28.8 lkg $tomato^{-1}$ (Table 3).

**Table 1** Life span of greenhouse and greenhouse materials (years)

| Materials | Life span |
|---|---|
| Greenhouse | 15 |
| Concrete | 15 |
| LDPE | 3 |
| PC | 15 |
| PE | 5 |
| Perlite | 3 |
| Polystyrene | 3 |
| PVC | 10 |
| Steel | 15 |
| Wire | 15 |

**Table 2** Structure processes included in the inventory. Values are total amount of material per hectare and without considering life span

| | Elements | Quantity ($ha^{-1}$) | Unit |
|---|---|---|---|
| Materials | | | |
| Concrete | Foundations and main path | 63.1 | $m^3$ |
| LDPE | Covering and floor | 3,786.7 | kg |
| PC | Walls | 1,707.3 | kg |
| PE | Insect-proof screens and plant gutter system | 1,633.6 | kg |
| PP | Raffia plant gutter system | 1,06.2 | kg |
| PVC | Clips and wedges | 1,226.7 | kg |
| Steel | Posts, frame reinforcements, gutters, axes, profiles, ventilators arches and plant gutter system | 76,994.0 | kg |
| Wire | Plant trellis system | 1,125.4 | kg |
| Processes | | | |
| LDPE | Extrusion and plastic film | 3,786.7 | kg |
| PC | Extrusion and plastic film | 1,707.3 | kg |
| PE | Extrusion and plastic pipes | 1,633.6 | kg |
| PP | Extrusion and plastic film | 1,06.2 | kg |
| PVC | Injection moulding | 1,226.7 | kg |
| Steel | Manufacturing processes | 76,994.0 | kg |
| Steel | Zinc (steel coating) | 4,651.6 | $m^2$ |
| Transport | Lorry, 605 km | 52,380.6 | tkm |
| Wire | Wire production | 1,125.4 | kg |

*LDPE* low density polyethylene, *PC* polycarbonate, *PE* polyethylene, *PP* polypropylene, *PVC* polyvinylchloride

Climate control system—as in most Mediterranean greenhouses, there was no heating system and only natural ventilation. Therefore, only the consumption of electricity for ventilator operation was taken into account, which was 50 kWh $ha^{-1}$, equivalent to 0.30 kWh t $tomato^{-1}$.

**Table 3** Auxiliary equipment processes included in inventory. Values are total amount of material per hectare and without considering life span

| | Elements | Quantity ($ha^{-1}$) | Unit |
|---|---|---|---|
| Materials | | | |
| LDPE | Bed plastic | 694.7 | kg |
| LDPE | Substrate bags | 275.0 | kg |
| PE | Pipes, drippers and microtubes | 418.0 | kg |
| PE | Pickaxes | 17.7 | kg |
| PE | Fertilizers tanks | 31.7 | kg |
| Perlite | Substrate | 18,876.5 | kg |
| Polystyrene | Substrate bed | 764.5 | kg |
| PVC | Distribution system | 439.7 | kg |
| Steel | Pumps and injectors | 79.7 | kg |
| Processes | | | |
| LDPE | Extrusion and plastic film | 694.7 | kg |
| LDPE | Extrusion and plastic film | 275.0 | kg |
| PE | Extrusion and plastic pipes | 418.0 | kg |
| PE | Injection moulding | 17.7 | kg |
| PE | Blow moulding | 31.7 | kg |
| Polystyrene | Foaming expanding | 764.5 | kg |
| PVC | Extrusion plastic and film | 439.7 | $m^2$ |
| Steel | Manufacturing processes | 79.7 | kg |
| Transport perlite | Lorry, 7 km | 134.1 | tkm |
| Transport auxiliary equipment | Lorry, 5 km | 12.2 | tkm |

Values are total amount of material per ha and without considering life span

*LDPE* low density polyethylene, *PE* polyethylene, *PVC* polyvinylchloride

Fertilizers—the total quantities of N, P and K were obtained from the different fertilizers applied to the crop. Due to the great variability of fertilizers used by growers, the use of generic values was considered in order to facilitate comprehension of their contribution to impact categories. The $NH_3$–N, $N_2O$–N and $NO_x$–N emissions to air and $NO_3$–N emissions to water were taken into account (Audsley et al. 1997; Brentrup et al. 2000) (Table 4). Emissions during the manufacturing processes were also included in the fertilizer stage.

Pesticides—the total amount of active ingredient was considered for insecticides (3.8 kg ha$^{-1}$) and fungicides (28.5 kg ha$^{-1}$). The manufacture of pesticides and the use of machinery for their application were also taken into account for the LCA, according to Green (1987) and Audsley et al. (2009).

Wastes management—several wastes material treatments were considered. Metal and polycarbonate wastes were 100 % recycled. Concrete and substrate were 50 % recycled and 50 % transported to landfill. Plastics were 90 % recycled and 10 % transported to landfill. Green biomass was treated at the compost plant, considering a 60 % loss of fresh weight at the time of transport. Only emissions due to transport to the landfill and composting plant, and emissions due to landfill disposal were included in the study. Transports to the recycling plants and recycling processes were not considered, following the cut-off method defined by Ekvall and Tillman (1997), recycling processes are allocated downstream in the cascade as a raw material for another product. According to this method, each product should only be assigned the environmental impacts directly caused by the use of that product.

Transport by lorry or van were included for most elements delivered to the greenhouse, considering vehicle and road manufacture, maintenance and diesel consumption.

**Table 4** Fertilizer doses and application emissions

| | kg ha$^{-1}$ |
|---|---|
| Fertilizers doses | |
| N | 798 |
| $P_2O_5$ | 506 |
| $K_2O$ | 1,562 |
| Air emissions | |
| $NH_3$-N | 24 |
| $N_2O$-N | 10 |
| $NO_X$-N | 1 |
| Water emissions | |
| N-$NO_3$ | 359 |
| P | 0 |

Values are total amount of material per ha

Transports of fertilizers and pesticides were not incorporated in the system since it was considered that these products came from a local supplier and were not an issue considered for improvement in this study. Transport in waste disposal is included under waste management.

In this study, we considered the current agricultural practice for a tomato crop in a multi-tunnel greenhouse in the south of Spain, established as the starting point for the alternatives analysis. Several potential alternatives were analysed for reduction of environmental impacts. The majority of improvements were oriented to the agricultural practice: reduction of the volume of substrate and extension of its life span; reduction of the amount of fertilizers, and extension of greenhouse life span. The purpose was to present feasible objectives that could be commonly applied for tomato crops.

Perlite substrate was one of the major burdens. Two alternatives were evaluated in the sensitivity analysis: a 5, 15, 25 and 35 % reduction of perlite volume, and extension of its life span up to 4 years.

For fertilizers, a 10, 20 and 30 % reduction in the amount applied to the crop was considered. In general, there is a tendency towards excessive fertilization in the Mediterranean area (Gallardo et al. 2009). Even with a 30 % reduction, the amount of fertilizers applied was within the range suggested for tomato crops (Muñoz et al. 2008).

Greenhouse life span was considered as 15 years as the baseline. However, it is common practice for most growers to extend the life span of the greenhouse frame (Pérez Parra et al. 2002) therefore a life span of 20 years was considered as a alternative.

The increased use of renewable energy in the production of electricity was another alternative taken into account. The 2009/28/CE Directive of the European Parliament establishes compulsory objectives for every member state for using renewable energies in the EU, to be achieved by the year 2020 (2009/28/CE 2009). As Spain claims that it will achieve its objective of 40 % renewable energy in the production of electricity (Ministerio de Industria, Turismo y Comercio 2009), the progress towards renewable energy in the production of electricity was included in the sensitivity assessment.

## 3 Results

### 3.1 Reference greenhouse LCIA

The results obtained in the life cycle impact assessment (LCIA) showed the environmental impacts in the tomato production system included in the inventory phase (Table 5). Since there was no need for a heating system in the greenhouse, greenhouse crop management had few direct energy

**Table 5** Stage contributions to selected impact categories for tomato production in a multi-tunnel greenhouse per ton of tomato

| IC | Unit | Total | Structure | Climate system | Auxiliary equipment | Fertilizers | Pesticides | Waste |
|---|---|---|---|---|---|---|---|---|
| AD | kg Sb eq | 1.7E+00 | 7.8E−01 | 1.1E−03 | 6.3E−01 | 2.0E−01 | 1.7E−02 | 2.3E−02 |
| AA | kg $SO_2$ eq | 1.0E+00 | 3.9E−01 | 1.5E−03 | 4.2E−01 | 2.1E−01 | 1.9E−02 | 1.2E−02 |
| EU | kg $PO_4^{-3}$eq | 4.9E−01 | 1.5E−01 | 2.7E−04 | 8.0E−02 | 2.5E−01 | 6.5E−03 | 3.9E−03 |
| GW | kg $CO_2$ eq | 2.5E+02 | 8.8E+01 | 1.5E−01 | 7.7E+01 | 8.2E+01 | 2.0E+00 | 3.1E+00 |
| PO | kg $C_2H_4$ | 5.4E−02 | 2.0E−02 | 5.4E−05 | 2.7E−02 | 4.9E−03 | 1.2E−03 | 1.0E−03 |
| CED | MJ | 4.0E+03 | 1.9E+03 | 3.1E+00 | 1.6E+03 | 3.9E+02 | 4.1E+01 | 5.7E+01 |

*AD* abiotic depletion, *AA* air acidification, *EU* eutrophication, *GW* global warming, *PO* photochemical oxidation, *CED* cumulative energy demand

inputs. The main burdens in the product system were the structure, auxiliary equipment and fertilizers.

The structure accounted for between 30 and 48 % of the contributions, depending on the impact category (Fig. 2). It was the major burden in abiotic depletion, 47 %; global warming, 35 %; and cumulative energy demand, 48 %, impact categories. Auxiliary equipment made the highest contributions to air acidification, 40 % and photochemical oxidation, 49 %, and the second highest burden to abiotic depletion, 38 % and cumulative energy demand, 40 %.

Fertilizers represented 51 % of the total contribution to eutrophication in the product system and were the second major contributor to global warming, accounting for 32 %. The other stages included in the tomato production system accounted for low contributions to the impact categories: waste management was responsible for between 0.79 and 1.9 %; pesticides between 0.80 and 2.1 %; and burdens of the climate system were negligible, with all values near 0 %.

The inputs for steel, plastics, concrete and transport processes were evaluated in the assessment of the structure. The large amount of steel in the frame had the highest values in the air acidification, eutrophication, global warming and photochemical oxidation impact categories, from 44 to 74 % (Fig. 3). Plastics were the main contributor to abiotic depletion and cumulative energy demand, both 59 % of the total, due to the large amount of oil and natural gas involved in the manufacture of plastics.

The principal burdens in the auxiliary equipment stage were substrate and consumption of electricity (Fig. 4). In the case of substrate, the perlite manufacturing process consumed a large amount of natural gas in the expansion of the mineral. As a result, the substrate had the highest scores in the abiotic depletion, global warming and cumulative energy demand impact categories (46 %, 51 % and 44 % of the total). The electricity consumption to operate the pumps, especially to bring water from the well, was the main contribution to the acidification and eutrophication impact categories, 60 % and 58 %, and the second to photochemical oxidation, 34 %. The contribution of plastics manufacture was the highest in photochemical oxidation, with a value of 36 %, due to the manufacturing process of polystyrene substrate beds. High emissions of pentane are released to the air during the foaming process for expansion of polystyrene.

Fertilizer environmental impacts were due to emissions during manufacture and to their application to the crop. Emissions during the manufacture of nitrogen fertilizers had the highest scores, between 52 and 64 %, in all the impact categories except for eutrophication (Fig. 5). Emissions due to the use of fertilizers were a major burden in

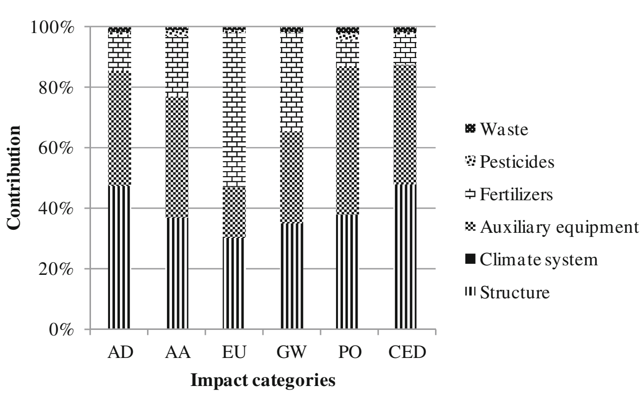



**Fig. 2** Stage contributions to selected impact categories for tomato production in a multi-tunnel greenhouse. *AD* abiotic depletion, *AA* air acidification, *EU* eutrophication, *GW* global warming, *PO* photochemical oxidation, *CED* cumulative energy demand

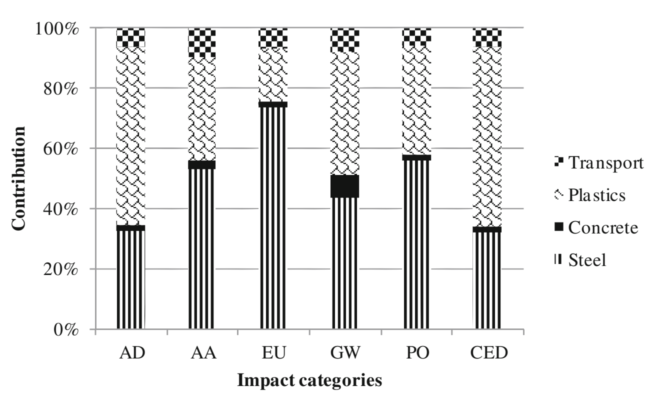



**Fig. 3** Structure processes contributions to selected impact categories. *AD* abiotic depletion, *AA* air acidification, *EU* eutrophication, *GW* global warming, *PO* photochemical oxidation, *CED* cumulative energy demand

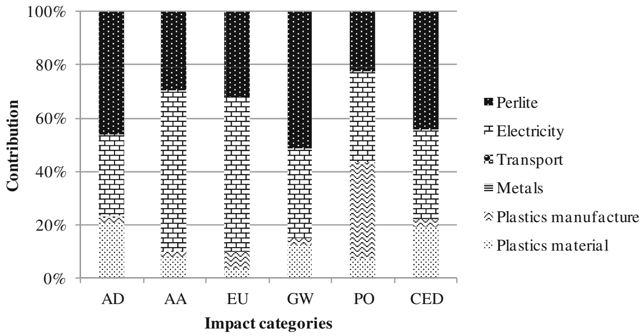



**Fig. 4** Auxiliary equipment contributions to selected impact categories. *AD* abiotic depletion, *AA* air acidification, *EU* eutrophication, *GW* global warming, *PO* photochemical oxidation, *CED* cumulative energy demand

eutrophication, contributing 89 %, mainly due to the estimated emissions to water. Emissions due to the application of fertilizers were also responsible for a contribution of 34 % to the global warming impact category, essentially caused by the emissions of dinitrogen monoxide by N-fertilizers.

The results obtained in the LCIA revealed the main environmental impacts in the tomato production system and served as the starting point for the assessment of alternatives.

### 3.2 LCIA of alternatives for improvement

The relevance of the results of the improvement alternatives were evaluated, conducting a specific LCIA for each one of them.

The environmental impacts of the reference situation were considered as 100 % to calculate the percentages of the alternatives (Table 6).

The present study assessed alternatives to reduce substrate contribution as this causes major environmental impacts in the auxiliary equipment stage. When the substrate volume was reduced by 25 %, the auxiliary equipment contributions to the impact categories more affected by the

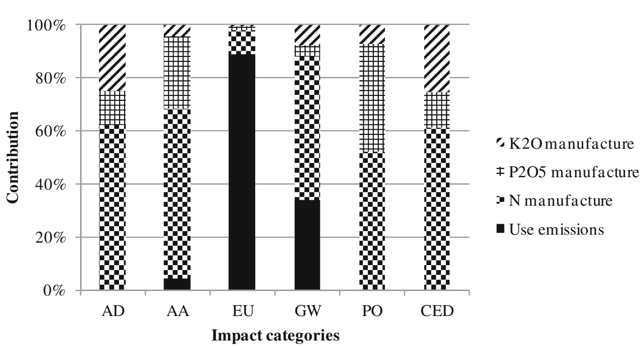



**Fig. 5** Fertilizer processes contributions to selected impact categories. *AD* abiotic depletion, *AA* air acidification, *EU* eutrophication, *GW* global warming, *PO* photochemical oxidation, *CED* cumulative energy demand

**Table 6** Contributions of the different inputs for improvement techniques versus the reference situation in the alternatives analysis (%) per impact categories (IC)

| IC | Fertilizers | Structure | Auxiliary equipment | | |
|---|---|---|---|---|---|
| | 30 % volume decrease | 20 years greenhouse life span | 25 % perlite decrease | 4 years perlite life span | 40 % renewable energy for electricity |
| AD | 70.0 | 89.1 | 89.3 | 88.5 | 83.7 |
| AA | 70.0 | 83.0 | 93.0 | 92.6 | 68.3 |
| EU | 70.0 | 79.5 | 92.4 | 92.1 | 70.6 |
| GW | 70.0 | 84.1 | 87.7 | 87.3 | 82.2 |
| PO | 70.0 | 83.2 | 94.7 | 94.4 | 81.9 |
| CED | 70.0 | 89.2 | 89.8 | 89.0 | 95.9 |

Results are related to fertilizers, structure and auxiliary equipment stages respectively, not to the global production system

*AD* abiotic depletion, *AA* air acidification, *EU* eutrophication, *GW* global warming, *PO* photochemical oxidation, *CED* cumulative energy demand

manufacture of perlite (abiotic depletion, global warming and cumulative energy demand) decreased by 10 to 12 %.

Considering a 4-year life span of substrate instead of 3 years, reductions of environmental impact categories were slightly higher than with a 25 % reduction of perlite volume. The life span extension affected not only perlite but also plastic bags for its containment and transport to the greenhouse and final disposal. Therefore, reductions of auxiliary equipment contributions with respect to the reference system were slightly higher, between 11 and 13 %, for the abiotic depletion, global warming and cumulative energy demand impact categories.

The fertilizer stage included processes directly related to the amount of product applied to the crop, such as manufacture, emissions to air and emissions to water due to their application. For this reason, contributions to all the impact categories were reduced by the same proportion as the reduction in the amount of fertilizer in the fertilizer stage. A 10 % reduction of fertilizers decreased contributions to the global production system by 0.89 to 5.1 % depending on the impact category. A 20 % reduction decreased contributions by 1.8 to 10.2 % and with a 30 % reduction of fertilizers, by 2.7 to 15 %.

Extension of greenhouse life span to 20 years reduced environmental impacts of the structure and waste management stages. Since structure was one of the principal burdens in the product system, this was the stage where the major reductions to all the impact categories were obtained, with percentages between 11 and 21 %.

Using renewable energy in the production of electricity does not depend directly on growers but it affects the environmental impacts of the tomato production system because of the electricity consumption for the irrigation and climate control systems. Increases of 10, 20, 30 and 40 % of

renewable energy were studied. With 40 % of renewable energy in the production of electricity there was a 4.1 % reduction in the auxiliary equipment contribution to cumulative energy demand, and between 16 and 32 % in the other environmental impact categories.

The different alternatives gave different reductions in each impact category. Radial plots illustrate the potential improvement of a specific alternative, showing the percentage improvement for each alternative in the global production system per impact category (Fig. 6). It can be seen that the contribution to most impact categories can be reduced by extending the greenhouse life span. Acidification and photochemical oxidation are strongly dependent on the use of electricity and consequently on its production. Environmental burdens of electricity production in Spain will be greatly reduced with increased use of renewable energy.

These analyses demonstrate (see Fig. 6) that eutrophication and global warming are mainly dependent on fertilizer reduction, the extensions of greenhouse and perlite life spans are important to reduce cumulative energy demand, and the increasing use of renewable energy and also the extension of greenhouse life span can contribute to reduce abiotic depletion, acidification and photochemical oxidation.

A best case, with a 25 % reduction in volume of perlite, extension of life span of perlite to 4 years, a 30 % reduction in volume of fertilizers, extension of greenhouse life span to 20 years and 40 % renewable energy used in the production of electricity, was found to give an 17 to 30 % reduction of contributions to the impact categories (Fig. 7).

## 4 Discussion

The objective of this study was to analyse the main environmental impacts of tomato production in a multi-tunnel greenhouse in Almeria and to present alternatives that can

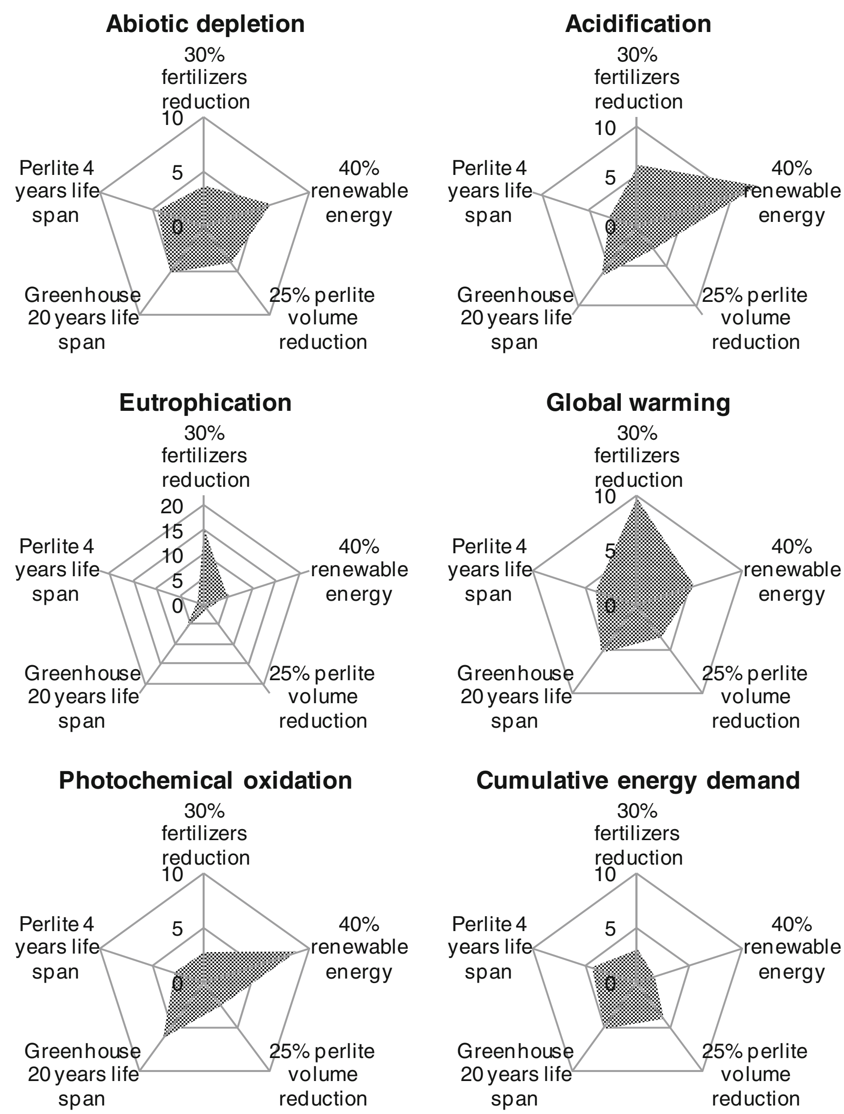



**Fig. 6** Radial plots representing percentage improvement for each alternative in the production system per impact category: 25 % reduction in perlite volume, 4 year extension of perlite life span, 30 % reduction of fertilizers volume, 20-year greenhouse life span and 40 % of renewable energy for electricity production

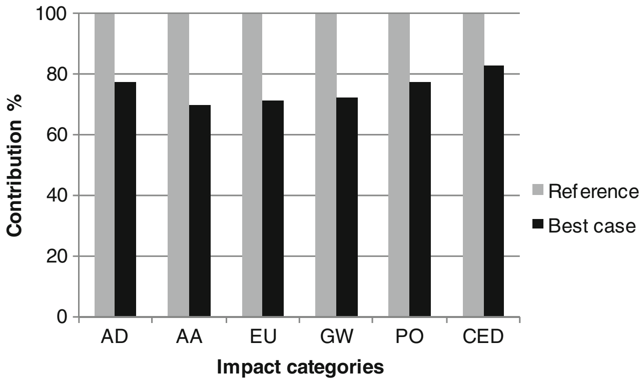



**Fig. 7** Contributions to impact categories of best case alternative vs. reference

contribute to reduce these impacts in greenhouse areas in the Mediterranean region. Although the 'parral' greenhouse is the most common on the coast of Almeria, the multi-tunnel greenhouse was used in this study, as high-technology greenhouses offer more opportunities to reduce inputs and increase productivity, using innovative developments and technologies or agricultural alternatives.

The LCA methodology proved to be a useful and objective tool to evaluate the environmental damage of this agricultural activity. The quantification of the potential reductions in environmental impacts demonstrates the most effective options to improve the environmental consequences of tomato production.

Here, we summarise the main points arising from the results, which showed that structure, auxiliary equipment and fertilizers contribute the largest environmental impacts in tomato production. These results were similar to those observed in previous studies in Mediterranean crops (Antón 2004; Romero-Gámez et al. 2009; Antón et al. 2005a). Data used by Antón (2004) referred to a tomato crop in the north of the Spanish Mediterranean coast, where the crop period is usually 6 months, from February to August. In contrast, the present study was on the coast of Almeria, where horticultural production in Spain is concentrated and crops are maintained for a longer period of time, from September to June. Therefore, the production cycle of the present study is more representative of the major surface area and production in Mediterranean crops.

Additional LCIA in the alternatives analysis showed the magnitude of the decrease in environmental impacts with the alternatives suggested. The importance of including farm infrastructure in the assessment was demonstrated as it was the major contributor to most impact categories. Unlike many industrial systems, low energy requirements in the cultivation process emphasized the impact of structure (Cowell 1998). Moreover, greenhouse life span is considerably shorter than that of industrial buildings.

Frame steel was the material responsible for the largest contribution. A detailed structural calculation of the supporting members could identify potential areas where steel could be saved, such as ventilators. Since the FU for the environmental impacts was the amount of tomatoes produced per unit ground area during the life time of the structure, environmental impacts of structure could be reduced by extending the greenhouse life span. When life span was estimated at 20 years, the structure environmental impacts were reduced by 6 % in the total production system. A longer greenhouse life span is possible, but this would require increasing the strength of the structure to withstand the extra loads (wind, snow, etc.) over a longer period of time. This structural calculation is beyond the scope of this paper.

Results from this study demonstrate that the inclusion of infrastructure is especially recommended in carbon footprint methods. In PAS-2050 2008, the greenhouse gas (GHG) emissions arising from the production of capital goods used in the life cycle of the product are currently excluded from the assessment of the GHG emissions of the life cycle of the product (PAS-2050 2008). This exclusion is a requirement of the method but it is not part of a better LCA. Treatment of the emissions is planned to be considered in future revisions of the PAS method.

There is considerable scope to enhance yields in Spain at the present moment, and technological improvements to increase productivity would directly reduce the environmental burdens per unit of produce. For example, yields of 20, 25 or 30 kg $m^{-2}$ would mean reductions of the inputs per FU of 17, 34 and 45 %, and consequently in the environmental impacts. These yields for classic tomato are currently achieved in greenhouses with improved ventilation (Baeza 2007).

In relation to the greenhouse auxiliary equipment, improvements should be oriented to reduce environmental impacts of substrate and electricity consumption.

Perlite entailed high environmental impacts due to the large amount of energy necessary in the manufacturing processes. Agronomic practices such as the reduction of substrate volume or extension of perlite life span to 4 years are options to reduce substrate environmental impacts (Diara et al. 2010). Currently, there are growers who extend perlite life span to 4 years. The alternatives analysis showed that a 25 % reduction in volume of perlite or extension of its life span to 4 years gave similar results. Both substrate-use alternatives entail root restriction, so an adjustment to nutrients and water supply should be taken into account (Xu and Kafkafi 2001). Studies on root restriction in horticultural practices conclude that a reduction of substrate volume is feasible without a significant lost of yield (Haghuis 1990; Logendra et al. 2001; Ganea et al. 2002). Further studies on reducing container size are needed to assure the feasibility of these alternatives. Alternative local materials or other substrates such as coconut fibre or rockwool

should also be studied in order to assess their contribution to environmental burdens in the tomato production system.

The results of fertilizers analysis showed their high environmental impacts due to manufacture and application to the crop. Nutrient solution runoff from greenhouse crops generally contains a high concentration of nitrogen, which is the factor contributing to eutrophication. (Muñoz et al. 2010) concluded that there are major contributions to eutrophication when different water sources are discharged to the watercourse. Efforts to decrease fertilizer environmental impacts could be oriented to reducing their dosage, better adjusting the fertilizers-water balance and implementing a closed-loop irrigation system. A 30 % reduction of fertilizers volume is feasible and highly recommended. This is within the suggested margins of fertilizers for tomato crops under Mediterranean climatic conditions, without causing any adverse effects on fruit yield or quality (Muñoz et al. 2008). Moreover, progress should focus on the methodologies currently used to assess the amount of fertilizer reaching the aquifers as they are only approximate and consequently the contribution of fertilizers to eutrophication is debatable.

The present study revealed how agricultural production can decrease environmental impacts by improvements in non-agricultural processes such as the increase of renewable energy in the production of electricity. The gross electricity production in Spain will include 40 % renewable energies in 2020 (Ministerio de Industria, Turismo y Comercio 2009). Efforts are oriented to increasing wind power and photovoltaic energy, so reducing the use of abiotic resources, and the impact of processes such as irrigation and ventilator operation, depending on electricity, will decrease.

In this study, toxicity of emissions was not evaluated. Although several methodologies for toxicity evaluation are available at the present moment, not any of them has enough consensus to be recommended. Scientific community is dedicating great efforts to clarify this problem. In this sense, USEStox (Rosenbaum et al. 2008) means an effort to harmonise all of them, but even though, international agreement has not been achieved for the characterisation factors in toxicity impact categories. Pesticide toxicity is a controversial issue that should require a deep analysis in a dedicated study, which is out of the scope of this one. Although waste management and pesticides were minor burdens in the total production system, because of the latest improvements in practice, attempts should be made to reduce their environmental impacts. In the case of pesticides, their environmental impacts should still be reduced to advance towards a more environmentally friendly and healthy production. Recently, covering plastic has begun to be used for 4 years in Almeria. Protected horticulture produces large amounts of solid waste (steel, plastics and green biomass) therefore material disposal should advance towards recycling and reuse of materials, especially for green biomass. Source segregation followed by composting of biodegradable matter is the best way to manage waste and reduce the impact for most of the impact categories considered (Antón et al. 2005b). A general consensus is needed for the most appropriate of the current methodologies to be used in LCA studies (Antón 2008). Moreover, land, water and other approaches in agricultural LCA would provide much more reliable and comprehensive information to environmentally conscious policy makers, producers, and consumers in selecting sustainable products and production processes (Roy et al. 2009).

## 5 Conclusions

Tomato production in a multi-tunnel greenhouse on the Mediterranean coast of Spain was studied in order to quantify the environmental impacts of this production process. Since there was no need for a heating system to warm the greenhouse, few energy inputs were involved in the greenhouse crop management. The main burdens in the product system were the structure, auxiliary equipment and fertilizers.

The present study served to assess and suggest alternatives of cleaner production in greenhouse areas. Reduction of fertilizer use would be the most efficient and economic way to improve the process environmentally. Since environmental impacts were referred to the amount of tomatoes produced per unit ground area during the useful life of the structure, an obvious way for reducing impacts would be by increasing the life span of the structure and by increasing productivity.

Further research should focus on assuring the feasibility of the suggested options and to develop innovative and technological tools to reduce inputs and their environmental impacts in agricultural production. The multi-tunnel greenhouse, as a high-technology installation, offers the possibility to accurately control the efficiency of any modification incorporated in the production system.

LCA proved to be an appropriate tool to accomplish the goals of the study. However, it could be improved by means of more accurate methods for the evaluation of eutrophication risk of fertilizers, toxicity of pesticides and water and land use.

**Acknowledgements** This work is part of the EUPHOROS research project, Efficient use of inputs in protected horticulture, FP7-KBBE-2007-1, financially supported by the EU and the INIA project, 'A comprehensive approach to greenhouse production and territory: promoting synergies towards sustainability and efficient energy use', RTA2008-00109-C03, funded by the Spanish government.

## References

2009/28/CE (2009) Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources

Antón A (2004) Utilización del Análisis del Ciclo de Vida en la Evaluación del Impacto ambiental del cultivo bajo invernadero Mediterráneo. Doctoral thesis, Universitat Politècnica de Catalunya, Barcelona

Antón A (2008) Sustainable management in horticulture: a life cycle perspective. In: The 8th International Conference on EcoBalance, Tokyo (Japan). Available from http://www.komatta-chan.jp/eco/index2.htm

Antón A, Montero JI, Muñoz P, Castells F (2005a) Identification of the main factors affecting the environmental impact of passive greenhouses. International Conference on sustainable Greenhouses Systems—Greensys2004, Leuven, Belgium. Acta Horticulturae 691:489–494

Antón A, Muñoz P, Castells F, Montero JI, Soliva M (2005b) Improving waste management in protected horticulture. Agron Sustain Dev 25:447–453

Audsley E, Alber S, Clift R, Cowell S, Crettaz P, Gaillard G, Hausheer J, Jolliet O, Kleijn R, Mortensen B, Pearce D, Roger E, Teulon H, Weidema B, van Zeijts H (1997) Harmonisation of life cycle assessment for agriculture. Final report, Concerted Action AIR3-CT94-2028. European Commission DG VI Agriculture, Silsoe

Audsley E, Stacey K, Parsons DJ, Williams AG (2009) Estimation of the greenhouse gas emissions from agricultural pesticide manufacture and use. Crandfield University. Available from https://dspace.lib.cranfield.ac.uk

Baeza E (2007) Optimización del diseño de los sistemas de ventilación en invernadero tipo parral. Doctoral thesis. Universidad de Almería. Escuela Politécnica Superior, Almería

Berger M, Finkbeiner M (2010) Water footprinting: how to address water use in life cycle assessment? Sustainability 2:919–944

Brentrup F, Küsters J, Lammel J, Kuchlmann H (2000) Methods to estimate on-field nitrogen emissions from crop production as an input to LCA studies in the agricultural sector. Int J Life Cycle Assess 5(6):349–357

CEN (2001) EN 13031. Greenhouses: design and construction—part 1: commercial production greenhouses. European Committee for Standardization. Available from http://www.cen.eu

Cowell SJ (1998) Environmental life cycle assessment of agricultural systems: integration into decision-making. Ph.D. thesis, University of Surrey, Guildford

Diara C, Incrocci A, Pardossi A, Minuto A Reusing greenhouse growing media. In: 28th International Horticultural Congress, Lisbon, Portugal, 22–27 August 2010 2010. International Society Horticultural Science. Acta Horticulturae

EFSA-PPR (2009) EFSA-PPR project on "Data-collection of existing data on protected crop systems (greenhouses and crops grown under cover) in Southern European EU Member States". Agricultural University of Athens. Available from http://www.efsa.europa.eu

Ekvall T, Tillman A (1997) Open-loop recycling, criteria for allocation procedures. Int J Life Cycle Assess 2(3):155–162

EUPHOROS (2008–2012) Efficient use of inputs in protected horticulture. Available from http://www.euphoros.wur.nl/UK/

FAO (2002) El Cultivo Protegido en Clima Mediterráneo. Organización de las Naciones Unidas para la Agricultura y la Alimentación, Roma. FAO Dirección de Producción y Protección Vegetal No 90. doi: ISBN 92-5-302719-3. Available from http://www.fao.org/docrep/005/s8630s/s8630s00.htm

Frischknecht R, Junblugth N, Althaus H-J, Doka G, Dones R, Heck T, Hellweg S, Hischeir R, Nemecek T, Rebitzer G, Spielmann M, Wernet G (2007) Overview and methodology. Ecoinvent report no 1. Swiss Centre for Life Cycle Inventories, Dübendorf, Switzerland

Fundación_Cajamar (2008) Análisis de la campaña Hortofrutícola de Almería, Campaña 2007/2008. Informes y Monografias. Available from http://www.fundacioncajamar.es

Gallardo M, Thompson RB, Rodríguez F, Fernández MD (2009) Simulation of transpiration, drainage, N uptake, nitrate leaching, and N uptake concentration in tomato grown in open substrate. Agr Water Manage 96:1773–1784

Ganea R, Indrea D, Apahidean AS, Apahidean M, Maniutiu D, Ficior D, Paven I (2002) Effect of composition and volume of substrate on yield and fruit quality of under glass grown tomatoes. Paper presented at the Buletinul Universitatii de Stiinte Agricole si Medicina Veterinara Cluj-Napoca. Seria Horticultura 57 Cluj-Napoca: University of Agricultural Sciences, Central Library (Exchanges)

Green MB (1987) Energy in pesticide manufacture, distribution and use. In: Helsel ZR (ed) Energy in plant nutrition and pest control, chapter 7., pp 165–177

Guinée JB, Gorrée M, Heijungs R, Huppes G, Kleijn R, de Koning A, Wegener Sleeswijk A, Suh S, Udo De Haes H, Bruijn H, Duin Rv, Huijbregts MAJ (2002) Handbook on life cycle assessment. Operational guide to the ISO standards. Eco-efficiency in industry and science. Kluwer, Dordrecht

Haghuis P (1990) Substrate. Reduction of mat volume for cucumbers is possible. Groeten en Fruit 46(16):32–33

ILCD (2010) International Reference Life Cycle Data System Handbook. European Commission. Joint Research Centre. Institute for Environment and Sustainability, 2010. Available from http://lct.jrc.ec.europa.eu/assessment/publications

INVERCA (2011) Invernaderos y Tecnología, S.A. Available from http://www.inverca.es/web/

ISO-14040 (2006) Environmental management—life cycle assessment—principles and framework. International Organisation for Standardisation ISO, Geneva

Jolliet O (1993) Bilan écologique de la production de tomates en serre. Revue S Vitic Arboric Hortic 25(4):261–267

Logendra LS, Gianfagna TJ, Janes HW (2001) Using mini-rockwool blocks as growing media for limited-cluster tomato production. HortTechnology 11(2):175–179

Ministerio Industria TyC (2009) Informe en relación con la cumplimentación del artículo 4.3 de la directiva 2009/28/CE, de 23 de abril de 2009, relativa al fometno del uso de energía procedente de fuentes renovables. Available from http://www.idae.es

Montero JI, Antón A, Torrellas M, Ruijs M, Vermeulen P (2011) Report on environmental and economic profile of present greenhouse production systems in Europe. European Comission. FP7-KBBE-2007–1 Project EUPHOROS (Reducing the need for external inputs in high value protected horicultural and ornamental crops). http://www.euphoros.wur.nl/UK

Muñoz P, Antón A, Paranjpe A, Ariño J, Montero JI (2008) High decrease in nitrate leaching by lower N input without reducing greenhouse tomato yield. Agr Sust Dev 28:489–495

Muñoz I, Gómez MM, Fernández-Alba AR (2010) Life cycle assessment of biomass production in a Mediterranean greenhouse using different water sources: groundwater, treated wastewater and desalinated seawater. Agr Syst 103:1–9

Nemecek T, Erzinger S (2005) Modelling representative life cycle inventories for Swiss arable crops. Int J Life Cycle Assess 10(1):1–9

Nielsen P, Nielsen A, Weidema B, Dalgaard R, Halberg N (2003) LCA food data base. Available from http://www.lcafood.dk

PAS-2050 (2008) Specification for the assessment of the life cycle greenhouse gas emissions of goods and services, vol ICS code 13.020.40. Carbon Trust, DEFRA and British Standard. Available from http://www.bsigroup.com

Pérez Parra J, López JC, Fernández MD (2002) La agricultura del Sureste: situación actual y tendencias de las estructuras de producción en la horticultura almeriense. In: JMc García Álvarez-Coque (ed) La Agricultura Mediterránea en el siglo XXI. Mediterráneo Económico. Instituto Cajamar, Almería

Romero-Gámez M, Antón A, Soriano T, Suárez-Rey E, Castilla N (2009) Environmental impact of greenbean cultivation: comparison of screen greenhouses vs. open field. Journal of Food Agric Environ 7(3&4):132–138

Rosenbaum RK, Bachmann TM, Swirsky Gold L, Huijbregts MAJ, Jolliet O, Juraske R, Koehler A, Larsen HF, MacLeod M, Margni M, McKone TE, Payet J, Schuhmacher M, van de Meent D, Hauschild MZ (2008) USEtox-the UNEP-SETAC toxicity model: recommended characterisation factors for human toxicity and freshwater ecotoxicity in life cycle impact assessment. International Journal of Life Cycle Assessment 13:532–546. http://dx.doi.org/10.1007/s11367-008-0038-4.

Roy P, Nei D, Orikasa T, Xu Q, Okadome H, Nakamura N, Shiina T (2009) A review of life cycle assessment (LCA) on some food products. J Food Eng 90:1–10

Stanghellini C, Kempkes FLK, Knies P (2003) Enhancing environmental quality in agricultural systems. In: Pardossi A, Serra G, Tognoni F (eds) International Symposium on Managing Greenhouse Crops in Saline Environment, Pisa (Italy), 9–12 July 2003. International Society Horticultural Science. Acta Horticulturae, pp 277–283

Stanhill G (1980) The energy cost of protected cropping: a comparison of six systems of tomato production. J Agr Eng Res 25:145–154

Van Woerden S (2001) The application of Life Cycle Analysis in glasshouse horticulture. In: International Conference LCA in Foods, Gothenburg, Sweden, pp 136–140

Williams AG, Audsley E, Sandars DL (2006) Determining the environmental burdens and resource use in the production of agricultural and horticultural commodities. Cranfield University and Defra. Defra Research Project IS0205. Available from http://www.silsoe.cranfield.ac.uk and http://www.defra.gov.uk

Williams A, Pell E, Webb J, Moorhouse E, Audsley E (2008) Consumption of fresh produce in the UK from Mediterranean countries and the UK. In: The 8th International Conference on EcoBalance, Tokyo, Japan. Available from http://www.komatta-chan.jp/eco/index2.htm

Xu G, Kafkafi U (2001) Nutrient supply and container size effects on flowering, fruiting, assimilate allocation, and water relations of sweet pepper. In: Bar-Tal A, Plaut Z (eds) World Congress on Soilless Culture: agriculture in the coming Millennium, Ma'ale Hachamisha, Israel. International Society Horticultural Science. Acta Horticulturae